

Identifying Glueball at 3.02 GeV

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Abstract

We examine the nature of the unknown enhancement around 3 GeV observed by the BABAR collaboration in the $m_{p\bar{p}}$ spectrum of the $\bar{B}^0 \rightarrow p\bar{p}D^0$ decay. After demonstrating that the peak can be neither identified as a charmonium state, such as η_c or J/ψ , nor classified as one of the light-flavor mesons, we conclude that it corresponds to a glueball fitted as $X(3020)$ with $(m_X, \Gamma_X) = (3020 \pm 8, 103 \pm 3)$ MeV, which could be the first glueball state above 3 GeV.

Introduction— The glueball (G) is a bound state that contains no valence quarks but gluons only. This is because gluons, which are charged with colors in QCD and force carriers to bind quarks becoming mesons and baryons, can also glue themselves together to form a bound state. Since it is a unique feature purely for the non-Abelian gauge fields, whether the existence of the gluon condensates can be well established or not appears to be a real test for QCD. In principle, the search for glueballs depends on gluon-rich processes, such as the radiative J/Ψ decays via $c\bar{c} \rightarrow \gamma gg$.

However, it is known that the glueball identifications are complicated [1–3]. With the predicted mass around 1.7 GeV [4, 5], the lightest $J^{PC} = 0^{++}$ scalar glueball is allowed to mix with nearby $q\bar{q}$ mesons in the spectrum. Since there are two states, $f_0(1500)$ and $f_0(1710)$, proposed to be composed of the glueball in different mixing scenarios [6], the identification is obscure. The lightest tensor glueball with $J^{PC} = 2^{++}$ is believed to have a mass close to 1.3 GeV in the MIT bag model [7] and 2.4 GeV in the lattice QCD calculation [4, 5]. If $M(2^{++}) = 1.3$ GeV, both $f_2(1270)$ and $f'_2(1525)$ as the ground states of the 2^{++} mesons are argued to have the 2^{++} glueball content [8]. On the other hand, if $M(2^{++}) = 2.4$ GeV [2], both $f_J(2220)$ ($J = 2$ or 4) [9, 10] and $f_2(2340)$ [11] are considered to be the candidates, whereas the existence of $f_J(2220)$ is not conclusive [12]. Unlike 0^{++} and 2^{++} , the difficulty to establish the lightest 0^{-+} pseudoscalar glueball is that the predicted $M(0^{-+}) \simeq 2.6$ GeV in the lattice QCD calculation [4, 5] has no correspondence with the data. Nonetheless, $\eta(1405)$ seems to be a perfect candidate [13]. Particularly, the unseen in $\gamma\gamma$ reactions [14] reflects that its components are gluons. In addition, $X(1835)$ first measured in the $J/\Psi \rightarrow \gamma p\bar{p}$ decays [15] is another possible glueball state [16] at a mass below 2 GeV. Interestingly, instead of taking the candidates as the pure glueballs, the $\eta - \eta' - G$ [17] and $\eta_c - G$ [18] mixing scenarios for $\eta(1405)$ and $X(1835)$ are able to allow their own glueball components to be at least 2 GeV, respectively. This alleviates the problem that the glueballs with masses smaller than 2.6 GeV. However, due to the two mixing scenarios, it is clearly difficult to draw a clear conclusion about the glueball state. Moreover, as the mesons lying between the glueball candidates are not necessarily well settled, it increases the uncertainty. As a result, it is unrealistic to say that the search for the lowest glueballs can provide a compelling evidence for their existences.

Since the searches for the three lightest glueball states are still unclear, we should move on to explore the heavier states. Presently, as the PANDA experiment built to scan heavy

glueballs with masses under 5.4 GeV will not be ready until 2018, we can only use the decays of the charmonium states, such as η_c , J/ψ and $\psi(2S)$, in the mass range of 3.0 – 3.7 GeV, where the glueballs with masses around 3 GeV have been richly predicted.

On the other hand, although the B meson decays are not regarded as the gluon-rich processes, they can be more beneficial to offer accesses to a wider detection range of heavy glueball productions. We note that the three-body baryonic $B \rightarrow p\bar{p}M$ decay with a two-step process $B \rightarrow (G \rightarrow p\bar{p})M$ could be an ideal channel, where M is the recoiled meson. In particular, one can think of the $G \rightarrow p\bar{p}$ transition as an inverse process of the $p\bar{p}$ annihilation, which has been used at LEAR and PANDA as a gluon-rich process to search for glueballs. In fact, the process of $B \rightarrow \xi K \rightarrow p\bar{p}K$ has been applied to constrain the narrow resonant state ξ , known as the glueball candidate $f_J(2220)$ [19, 20]. Recently, the BABAR collaboration has observed an unknown enhancement at 3.0 – 3.1 GeV in the $m_{p\bar{p}}$ spectrum of $\bar{B}^0 \rightarrow p\bar{p}D^0$ [21]. We shall demonstrate that the peak is a sign for a resonant state as it is unable to be reproduced by the perturbative QCD (pQCD) calculations. Since the charmonium states, such as η_c and J/ψ as well as the light-flavor mesons are not favored, we have to introduce the glueball state at a mass above 3 GeV as the resonant state.

Data Analysis— For the $m_{p\bar{p}}$ spectrum in the $\bar{B}^0 \rightarrow p\bar{p}D^0$ decay, the data around 3 GeV measured by the BABAR collaboration [21] are robust as the highest data point is about 5σ significance away from zero. We emphasize that the peak at 3 GeV can only be revealed when the $m_{p\bar{p}}$ spectrum is split into two parts in terms of $m_{Dp} > 3$ and < 3 GeV, respectively [21]. We note that the threshold effect that shadows other peaking signals has been removed to the $m_{p\bar{p}}$ spectrum according to $m_{Dp} > 3$ GeV.

To find out if the peak at 3 GeV can be accounted in the theory without introducing a new state, we start with the amplitude based on pQCD counting rules, given by [22]

$$\mathcal{A}(\bar{B}^0 \rightarrow p\bar{p}D^0) = \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* a_2 \langle D^0 | (\bar{c}u)_{V-A} | 0 \rangle \langle p\bar{p} | (\bar{d}b)_{V-A} | \bar{B}^0 \rangle, \quad (1)$$

where G_F is for the Fermi constant, V_{cb} and V_{ud} represent the CKM matrix elements for the $b \rightarrow c\bar{u}d$ transition at the quark level, and $(\bar{q}_1 q_2)_{V(A)}$ stands for $\bar{q}_1 \gamma_\mu (\gamma_5) q_2$. For the D meson production, we have

$$\langle D^0 | (\bar{c}u)_{V-A} | 0 \rangle = i f_D p^\mu, \quad (2)$$

where f_D is the decay constant of D . The matrix elements for the $\bar{B}^0 \rightarrow p\bar{p}$ transition are

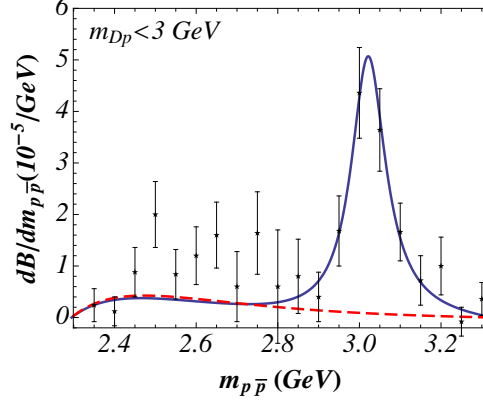


FIG. 1. Invariant mass spectrum as the function of the invariant mass $m_{p\bar{p}}$ in $\bar{B}^0 \rightarrow p\bar{p}D^0$, where the data points are taken from Ref. [21], the solid line includes the contributions from the resonance and pQCD counting rules, and the dashed line corresponds to that without any resonance state.

parameterized as [23]

$$\begin{aligned}\langle p\bar{p}|\bar{d}\gamma_\mu b|\bar{B}^0\rangle &= i\bar{u}[g_1\gamma_\mu + g_2i\sigma_{\mu\nu}p^\nu + g_3p_\mu + g_4q_\mu + g_5(p_{\bar{p}} - p_p)_\mu]\gamma_5v, \\ \langle p\bar{p}|\bar{d}\gamma_\mu\gamma_5 b|\bar{B}^0\rangle &= i\bar{u}[f_1\gamma_\mu + f_2i\sigma_{\mu\nu}p^\nu + f_3p_\mu + f_4q_\mu + f_5(p_{\bar{p}} - p_p)_\mu]v,\end{aligned}\quad (3)$$

where $p = p_B - p_p - p_{\bar{p}}$ and $q = p_p + p_{\bar{p}}$ with p_i ($i = B, p, \bar{p}$) representing the momenta of the particles, and the form factors $f_j(g_j) = D_{f_j(g_j)}/t^n$ ($j = 1, 2, \dots, 5$) with $t = m_{p\bar{p}}^2$ are in accordance with pQCD counting rules [24], such that the form of $1/t^n$ with $n = 3$ is to count the number of the hard gluons for the $B \rightarrow p\bar{p}$ transition [25]. The theoretical inputs for a_2 , f_D , and $D_{f_j(g_j)}$ can be referred to those in Ref. [22]. To integrate over m_{Dp} in the range < 3 GeV, we use the equation in Ref. [26] for the phase space of the three-body decay. Our result is shown in Fig. 1.

As seen in Fig. 1, the dashed line in the $m_{p\bar{p}}$ spectrum fits with the flatness of the non-peaking data points given in Ref. [21], which illustrates the suppression featured by $f_j(g_j) \propto 1/t^3$ in pQCD. For the data points unlinked by the dashed line, we suspect that they are not related to any resonances as the significances are less than 2σ [27]. Since the fit with only pQCD counting rules fails to reproduce the enhancement around 3 GeV, a resonant state at the peak is suggested. As $\bar{B}^0 \rightarrow (M(c\bar{c}) \rightarrow p\bar{p})D^0$ is allowed to take place, with the mass of M around 3 GeV, J/ψ or η_c can be the candidate for the resonance. In Eq. (3), the $\bar{B}^0 \rightarrow p\bar{p}$ transition is via $\bar{B}^0(b\bar{d}) \rightarrow (d\bar{d} \rightarrow p\bar{p})$. In pQCD counting rules, one needs three hard gluons for the transition: one hard gluon is to speed up \bar{d} , while the other

two attach to the valence quarks inside $p\bar{p}$. Without being directly related to $p\bar{p}$ by the hard gluons, the $d\bar{d}$ pair can be bounded as the light-flavor meson $M(d\bar{d})$. It is also possible for the $d\bar{d}$ annihilation, such that the multi-gluons are generated to form the glueball G at a mass around 3 GeV. Therefore, we have three possibilities: the charmonium $M(c\bar{c})$ such as J/ψ and η_c , the light-flavor meson $M(d\bar{d})$, and the glueball G .

As a W -boson exchange process, $\bar{B}^0 \rightarrow (M(c\bar{c}) \rightarrow p\bar{p})D^0$ is naturally suppressed. With the relation, given by

$$\mathcal{B}(\bar{B}^0 \rightarrow (J/\psi \rightarrow p\bar{p})D^0) \simeq \mathcal{B}(\bar{B}^0 \rightarrow J/\psi D^0)\mathcal{B}(J/\psi \rightarrow p\bar{p}), \quad (4)$$

we first test the resonant J/ψ state by taking the measured data in Fig. 1 and $\mathcal{B}(J/\psi \rightarrow p\bar{p})$ in [26] as the inputs. It turns out that $\mathcal{B}(\bar{B}^0 \rightarrow J/\psi D^0) \simeq 10^{-2}$, which strongly disagrees with the predicted $\mathcal{B}(\bar{B}^0 \rightarrow J/\psi D^0) \simeq 10^{-6}$ [28, 29] as well as the experimental upper bound $\mathcal{B}(\bar{B}^0 \rightarrow J/\psi D^0) < 10^{-5}$ [26]. In addition, it is stated in Ref. [21] that the decay width $\Gamma(J/\psi) = 93$ keV is not consistent with the broad 100-200 MeV in the $m_{p\bar{p}}$ spectrum. Similarly, we also obtain $\mathcal{B}(\bar{B}^0 \rightarrow \eta_c D^0) \simeq 10^{-2}$, which is much larger than the predicted $\mathcal{B}(\bar{B}^0 \rightarrow \eta_c D^0) \simeq 10^{-5}$ [29]. Clearly, the resonance cannot be the charmonium.

For $\bar{B}^0 \rightarrow (X \rightarrow p\bar{p})D^0$ with X to be $M(d\bar{d})$ or G , the relevant amplitude is the same as in Eq. (1), while the matrix elements of the $\bar{B}^0 \rightarrow p\bar{p}$ transition are given by

$$\langle p\bar{p} | (\bar{d}b)_{V-A} | \bar{B}^0 \rangle = \langle p\bar{p} | X \rangle \frac{i}{(t - m_X^2) + im\Gamma_X} \langle X | (\bar{d}b)_{V-A} | \bar{B}^0 \rangle, \quad (5)$$

where m_X and Γ_X are the mass and the decay width, respectively. Consequently, the relevant amplitude of $\bar{B}^0 \rightarrow (X \rightarrow p\bar{p})D^0$ now reads

$$\mathcal{A}_R(\bar{B}^0 \rightarrow (X \rightarrow p\bar{p})D^0) = \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* a_2 \frac{f_D}{(t - m_X^2) + im_X \Gamma_X} \bar{u}(a + b\gamma_5)v, \quad (6)$$

with the constants a and b . We note that, no matter what spin the X particle has, the parameterization for the $\bar{B}^0 \rightarrow (X \rightarrow p\bar{p})$ transition can be factored into a and b . Although a and b are in principle energy-dependent, their values can only be slightly changed with the deviation for the decay width around 100-200 MeV compared to the energy range at 3 GeV. Since the parity determination for the X particle is uncertain, we set $|a| = |b|$. By taking the 6 neighboring data points for the enhancement around 3 GeV as our inputs to the combined amplitude $\mathcal{A} = \mathcal{A}(\bar{B}^0 \rightarrow p\bar{p}D^0) + \mathcal{A}_R(\bar{B}^0 \rightarrow (X \rightarrow p\bar{p})D^0)$, we fit $|a| = |b|$,

the mass, and decay width for the X particle to be

$$|a| = |b| = 4.7 \pm 0.9, \\ (m_X, \Gamma_X) = (3020 \pm 8, 103 \pm 3) \text{ MeV}, \quad (7)$$

respectively, where the small errors correspond to the accuracies. Our result with the above resonance is presented as the solid line in Fig. 1. From the figure, we observe that it can fully explain the peak.

Due to its mass, $X(3020)$ is not likely to be $M(d\bar{d})$. In fact, there is no observation of any light-flavor meson heavier than $f_6(2510)$ in the literature [26], and the predicted spectrum of the excited mesons does not span above 2.8 GeV [30]. This agrees with the study of the hadronic Regge trajectories [31], where the mass limits are given to be (2.86 ± 0.11) and (3.10 ± 0.11) GeV for $n\bar{n}$ and $s\bar{s}$ mesons, respectively. Moreover, the heavier meson with the quark pair inside in the higher state has more decay channels, resulting in a broader decay width. Since $f_6(2510)$ has its decay width of (283 ± 40) MeV, it is also impossible for the heavier $M(d\bar{d})$ to shrink the width back to (103 ± 3) MeV. As stated in Refs. [32, 33], the glueball can be ideally observed in the mass range above 3 GeV, where the productions of the light-flavor mesons are not able to take place. As a result, it is reasonable to recognize $X(3020)$ as the glueball. Furthermore, it is promising that $X(3020)$ can be one of the glueballs predicted from various QCD models [4, 5, 33–36] in Table I, where the 2^{-+} glueball

TABLE I. Predicted glueballs around 3 GeV in Refs. [4, 5, 33–36], where the units of masses is in MeV.

$J^{PC} = 2^{-+}$	1^{--}	1^{+-}
$3100 \pm 30 \pm 150$ [4]	3200 ± 200 [34]	$2940 \pm 30 \pm 140$ [4]
$3040 \pm 40 \pm 150$ [5]	$3240 \pm 330 \pm 150$ [35]	$2980 \pm 30 \pm 140$ [5]
2950 ± 150 [34]	3020 [36]	3270 ± 340 [33]

contains 2 gluons, while the 1^{--} and 1^{+-} ones are allowed to have 3 constituent gluons. Since $J/\psi(1^{--})$ mainly decays into ggg , the $\mathcal{O} - J/\psi$ admixture with \mathcal{O} denoting the 1^{--} glueball is proposed to provide the solution to the so-called $\rho\pi$ puzzle [37]. Recently, the experimental data from the charmonium decays at BES and CLEOc turn out to disfavor this solution [38]. Nonetheless, one of the original mixing scheme leads to $|m_{\mathcal{O}} - m_{J/\psi}| < 80$ MeV and $\Gamma_{\mathcal{O}} < 120$ MeV [39], agreeing with the fits in Eq. (7). Finally, it is interesting to point out that

the same resonance also appears in $\bar{B}^0 \rightarrow p\bar{p}D^{*0}$ [21]. The combination of the two sets of data should be statistically more convincing.

Discussions and Conclusions— The baryonium is an alternative to explain $X(3020)$, while the baryon pair $\mathbf{B}\bar{\mathbf{B}}$ in the \bar{B}^0 transition are bounded before the $p\bar{p}$ production. For example, it can be the $p\bar{p}$ bound state as proposed to explain $X(1835)$ [40] except that the binding is in a higher state for a heavier mass. The excited $N^*\bar{N}^*$ bound state with N^* being one of the states $N(1440)$, $N(1520)$ and $N(1535)$ is also possible, provided that it is allowed to release energy to turn itself to be $p\bar{p}$. As one of the possible resonant baryoniums, the $\Lambda(1520)\bar{\Lambda}(1520)$ bound state is nearby $X(3020)$, but with more suppression by the $s\bar{s} \rightarrow u\bar{u}$ transition compared to the $N(1520)\bar{N}(1520)$ bound state. Due to the lack of the theoretical understanding, the discrimination among the baryoniums is not an easy task. Hence, from the theoretical consideration, the glueball seems to be the most promising candidate to understand the resonance in Eq. (7).

In sum, we have identified the existence of the glueball state at 3.02 GeV based on the peak in the $m_{p\bar{p}}$ spectrum of $\bar{B}^0 \rightarrow p\bar{p}D$ for $m_{Dp} < 3$ GeV observed by the BABAR collaboration, which could be the first glueball state above 3 GeV. Explicitly, it has been fitted to be $X(3020)$ with $(m_X, \Gamma_X) = (3020 \pm 8, 103 \pm 3)$ MeV.

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